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# THE FAIR SIS100 ACCELERATING RF STATION

H. G. Koenig, R. Balss, H. Klingbeil[1], U. Laier, D.E.M. Lens, P. Spiller, GSI, Darmstadt, Germany
K.Dunkel, M.Eisengruber, J.Hottenbacher, RI Research Instruments GmbH, B. Gladbach, Germany
G. Blokesch, C. Hiltbrunner, F. Wieschenberg, Ampegon AG, Turgi, Switzerland
[1]also at Technische Universität Darmstadt, Darmstadt, Germany

*Abstract*

For the Facility for Antiproton and Ion Research (FAIR) 14 ferrite loaded accelerating RF stations are planned for the first stage of realization of the SIS100 synchrotron. Each RF station has to provide a total peak gap voltage of up to 20 $kV_p$ in CW operation - tuneable in the range of 1.1 MHz up to 3.2 MHz to allow ion beam acceleration and beam gymnastics at different harmonic numbers and energy levels in the new facility.

Each RF station consists of a tuneable ferrite cavity, a single ended tetrode amplifier and a dedicated power supply and control unit (PSU) – including two bias current supplies for cavity- and control-grid(G1)-circuit-tuning. The ferrite cavity is based on the SIS18 cavity concept but has to provide a 1.25 times higher gap voltage of 20 $kV_p$ over a total length of 3 meters.

The realization is done by a consortium consisting of RI Research Instruments GmbH as consortium leader and manufacturer of the cavity, Ampegon PPT GmbH (for the tetrode amplifier) and Ampegon AG (for the power supply unit). In this contribution, the system design is discussed, and commissioning results are presented. All main parameters are achieved with the RF station described.

## INTRODUCTION

The acceleration stations belong to the key components of the new FAIR SIS100 Synchrotron, which is now under construction [1]. In a ring of about 1083.6 m in circumference ions of hydrogen up to uranium for a variety of different experiments will be accelerated. For this task, initially 14 tuneable and synchronised ferrite cavities shall be installed in several sectors. Our existing GSI SIS18 Synchrotron will be acting as a booster stage between the linear accelerator GSI UNILAC and the FAIR SIS100.

## GENERAL RF REQUIREMENTS

The 14 RF stations in the accelerator ring must provide a total accelerating voltage up to 280 kVp at the specific harmonic number of h=10. This led to the following requirements which are listed in the detailed specification for a single RF accelerating station:

### *General Data*

- Continuous wave operation (CW)
- Frequency range from 1.1 MHz to 3.2 MHz
- Tuning rate ≥ 10 MHz/s
- Nominal voltage of 20 $kV_p$
- Harmonic distortion < -26 dBc
- Impedance seen by the beam < 2 kΩ
- Cavity length 2998 mm

## CAVITY DESIGN

The cavity design (Fig. 1) is based on the classical approach for tuneable ferrite cavities e. g. the SIS18 type at GSI [2]. Its frequency range is reduced to < 50 % regarding the nominal span of the SIS18 accelerating system (from 0.8 to 5.4 MHz). The resonator consists of two coaxial resonators, working in push-pull mode onto a common accelerating gap. The two sections of the cavity are, for the most part, filled with ferrite material (Fig. 2). The resonant frequency of the cavity is controlled by DC bias magnetisation of the ferrite material in parallel to the rf. Six figure-of-eight or cross-coupled bias windings designed for DC currents up to 220 A are used for this purpose. The cavity deals with the known problems like Quality Loss Effect (QLE), Dynamic Loss Effect (DLE) mentioned in [3] and with moderate thermal degradation.

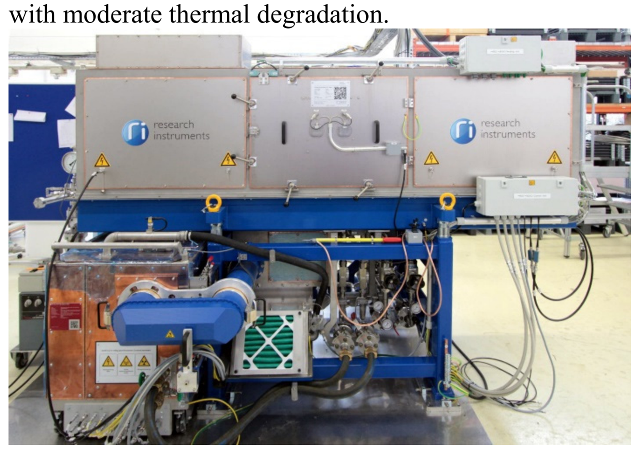

Figure 1: Complete RF station at the manufacturer site.

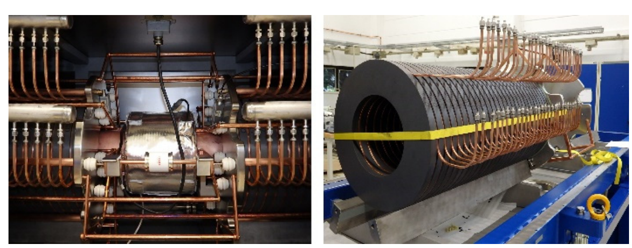
Figure 2: (l) Gap area – with heat-jacket for bakeout, (r) Ferrite stack – left side with cooling plates.

### *Ring Cores*

For the inductive load of the cavity a modified Ni-Zn-ferrite FXC8C11 by FERROXCUBE (Poland) – named as FXC8C15 - was chosen. 32 ferrite toroids are located on each side of the ceramic gap. Each toroid (T498/270/25) was tested and verified up to 350 $V_p$ in the desired frequency range in a 2-core test resonator – see Fig. 3 (l).

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Figure 3: (l) Ring core test set-up - ($L_{test}$+$L_{ref}$) || 10nF, (r) Partially coated ferrite stack (bottom down).

In Fig. 4 the test results of all 64 toroids are presented in one diagram. At first it shows the wide variation of the main property $R_p$ between the three test frequencies (green region). It shows also the degradation by DLE - exemplary tested at a slope rate of 100 MHz/s (orange region). The dynamic loss is reported in [3] and might be seen as a critical issue – but we can still accept values down to 40 Ω per ring core including a temperature-related drop. Figure 4 shows the deviations in core inductance $L_p$ - represented in a frequency shift - calculated from the deviation of the required bias current. The red curve in Fig. 4 shows the corresponding bias excitation.

Table 1: Mean Values of the Used Ferrites

| Freq. | unbiased | 1.1 MHz | 2.2 MHz | 3.2 MHz |
|---|---|---|---|---|
| $R_p$ / Ω | 84.7 ± 8 | 78.1 ± 7 | 88.6 ± 7 | 71.9 ± 6 |
| $L_p$ / µH | 1.77±0.138 | 1.15±0.153 | 0.27±0.004 | 0.13±0.003 |

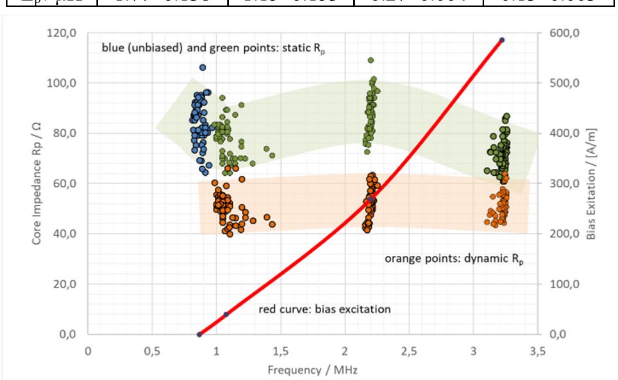


Figure 4: Ring core statistics and bias excitation.

Due to the high magnetic RF excitation up to 19 mT×MHz and the corresponding stored energy, the risk of quality loss effect (QLE) was taken into account. First tests show the occurrence of QLE at gap voltages >14 $kV_p$ [Fig. 5 (l)]. To increase the onset level of QLE the ferrite toroids were coated subsequently with approx. 0.3 mm bituminous paint to damp the magneto-elastically coupled acoustical modes along the outer circumference - following the idea in [4]. Partly the coating had to be done during the assembly – see Fig. 3 (r). After this measure the onset voltage of QLE was shifted to 18 $kV_p$, as shown in Fig. 5 (r). The inner bore was left uncovered so the QLE might be better controllable by coating these surfaces, too. As an ad hoc solution the additional gap capacitor was removed as noted in [2]. Now the cavity shows no noteworthy QLE also above its specified gap voltages > 20 $kV_p$. Other observed time-dependent losses might be of different nature and have to be studied later.

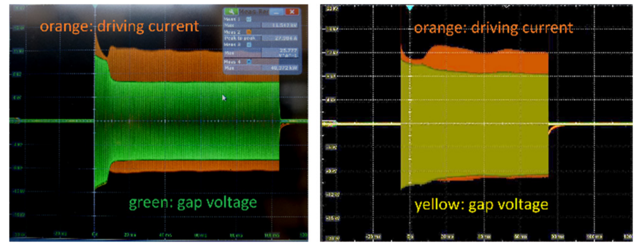


Figure 5: Voltage profile before (l) and after coating (r).

## AMPLIFIER

One single Tetrode RS2054SK (Thales, ex Siemens) is sufficient to drive the cavity. A ground-based cathode circuitry was chosen. The power amplifier is housed in a removable cart. To disconnect the amplifier from the cavity a U-shaped coaxial connector has to be removed. For an easy handling all electrical wirings between the amplifier and the cavity – as well as the air and water connections for cooling - are placed on the front.

### *Tuning System and Feedback Loop*

The power amplifier is equipped with a passive feedback loop. At first the input voltage of the driver is doubled by an input transformer 1:2. The cavity's RF voltage measured at one single ring core is subtracted from the input voltage via a second transformer 1:0.4 in series. In parallel a tuneable inductor allows the 50 Ω matching of the resonant control grid circuit to minimize reflected power on the input transmission line. The tuning of this grid resonator is done by a small DC power supply working as a slave device controlled by the main cavity biasing system. For the First of Series (FoS) a linear weighting between the biasing currents was intended. Figure 6 shows the effect of the active damping by the feedback loop. Stopping the RF burst leads to an in-phase cathode current driven by the cavity as source. During the voltage decay the quotient V/I represent the amplifier's output resistance $R_{amp}$ – in the given case $R_{amp} \approx 570$ Ω - instead of 1.7 kΩ without feedback. Due to the tetrode characteristic the closed-loop gain is decreasing at lower voltages and the output impedance increases again.

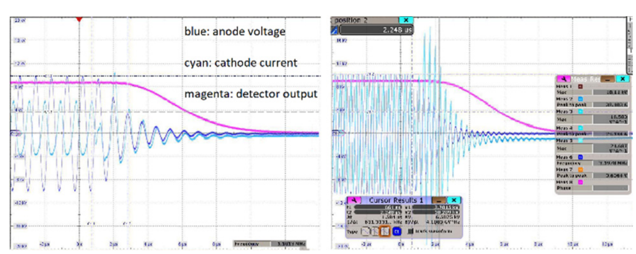


Figure 6: Active damping of the cavity (1.1&3.2MHz).

Table 2: Filling Time & Cavity's Impedance to the Beam

| frequency [MHz] | rise time to τ 1-1/e [µs] | $R_{p(b)}$ [kΩ] = $\tau/(2C_p)$ | $R_{p(b)}$ [kΩ] = $4R_{amp}\|\|R_p$ |
|---|---|---|---|
| 1.1 | 1.06 | 1.558 | 1.60 |
| 2.2 | 1.42 | 2.088 | 1.80 |
| 2.8 | 1.08 | 1.588 | 1.52 |
| 3.2 | 1.24 | 1.823 | 1.20 |

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## POWER SUPPLY UNIT (PSU)

Ampegon's modular anode power supply was designed for 17 $A_{dc}$ @ 14 kV. Nevertheless, the maximum requested output power is limited by the maximum anode power dissipation of the RS2054SK (~120 kW). In controlled PWM mode the anode voltage can be as low as possible regarding zero screen grid current without a tendency to voltage drops. A ± 20 % drift at mains input can be counterbalanced. During commissioning two operating points were set: 1) 5 $A_{dc}$ at 13 $kV_{dc}$ anode voltage - equivalent to 60 kW plate dissipation and 2) 7.5 $A_{dc}$ at 12.5 $kV_{dc}$ - equivalent to 90 kW for beam load simulation (+30 kW). At maximum load (20 $kV_p$ at 3.2 MHz) the cavity absorbs around 60 kW – the readout of the power meter at mains gives 130 kW. In total, the efficiency of the RF station is nearly 50 %. Under these conditions the power amplifier is operated in AB mode and by 100 % load alternation the cyclic input power changes are < 30 %. The auxiliary bias current sources for the ferrite tuning are chosen of the shelf. To dump the stored energy in the magnetic DC field three power diodes are added in series.

Table 3: PSU Design Data

| Power Supply | Voltage | Max. Current |
|---|---|---|
| Anode | 10 $kV_{dc}$ to 15 $kV_{dc}$ | 17 A |
| Screen Grid | 1700 $V_{dc}$ | 2.35 A |
| Control Grid | -650 $V_{dc}$ | 0.32 A |
| Filament | 360 $V_{ac}$ | 10 A |
| Cavity Bias | 18 $V_{dc}$ | 220 A |
| G1 Bias | 10 $V_{dc}$ | 10 A |

## COMMISIONING RESULTS

The presented RF station meets the requirements for the SIS100 synchrotron. Main results are listed below:

- The nominal gap voltage of 20 $kV_p$ (+10%) was achieved over the frequency range in CW operation.
- By the feedback loop the gap impedance to the beam was kept below 2 kΩ - also for lower gap voltages.
- No spurious resonances were seen up to the 6$^{th}$ order and no harmonic distortion exceeds -35 dBc.
- Full span ascent ramp rate is possible with 85 MHz/s – in triangle modulation ± 10 MHz/s as specified.
- Mains power input remained below 130 kW during CW operation at maximum voltage and frequency – including beam load overhead.
- The system's reliability was verified with 3 × 12 h continuous operation (endurance test, see Fig. 7)

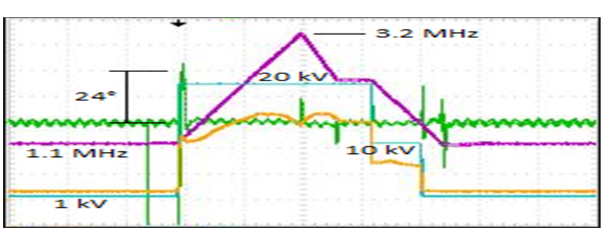


Figure 7: Voltage and frequency ramps of endurance test (cyan: Voltage; magenta: Frequency; yellow: Amplitude of controller output; green: Tracking error).

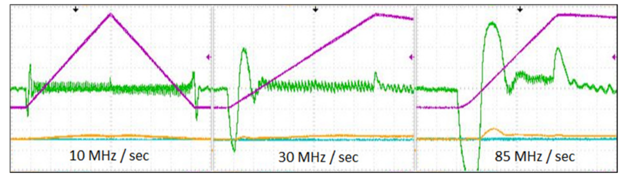


Figure 8: Full frequency slopes with tracking error (magenta: Frequency; green: Phase 12°/div).

## CONCLUSION AND FUTURE STEPS

The first accelerating RF station was assembled and tested successfully at the manufacturer's site. The station will subsequently be qualified at FAIR/GSI under all possible aspects before releasing the full series production. These tests will include especially more of our LLRF components in interaction with the power device – particularly with regards to the defined SIS100 machine cycles. Therefore it is foreseen to operate the station permanently in our test premises as a workhorse. This is also beneficial to uncover unknown problems. In parallel to the series production the FoS station may act as a reference. Beside the perfect results covering the SIS100 requirements the presented cavity is the first one with QLE damping. Unfortunately, the effectiveness was not as large as expected. It might be possible to increase the effectiveness by coating the inner bore too. A fast semiconductor gap switch is not yet available – nevertheless some space for mounting is reserved in the gap area. In addition, or as an alternative a fast detuning system could be employed by replacing the damping diodes by a controllable electronic load. The transferred power to the beam was simulated by switching between the two operating points cited above. For the Site Acceptance Test (SAT) a 'simulation' of the transfer power might be realised by a periodical detuning of the cavity.

## ACKNOWLEDGEMENT

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